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Y. Ham, S. Sitaraman, R. Swan, H. Lorenzana

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PDET-A New Tool for Partial Defect Verification of Pressurized Water Reactor Spent Fuel Assemblies

Y. Ham, S. Sitaraman, R. Swan and H. Lorenzana
Lawrence Livermore National Laboratory
Livermore, CA, USA

ham4@llnl.gov

Abstract. Lawrence Livermore National Laboratory (LLNL) has developed a novel methodology for detecting partial removal of fuel from pressurized water reactor (PWR) spent fuel assemblies. The methodology involves inserting tiny neutron and gamma detectors into the guide tubes of a spent fuel assembly and measuring the signals. The guide tubes form a quadrant symmetric pattern in the various PWR fuel product lines and the neutron and gamma signals from these various locations are processed to obtain a unique signature for an undisturbed fuel assembly. Signatures based on the neutron and gamma signals individually or in a combination are developed. Removal of fuel pins from the assembly causes the signatures to be visibly perturbed thus enabling the detection of diversion. The methodology has been proven to be effective in detecting as few as 10% missing pins in an assembly and without any fuel movement and operator provided information. In this paper, we present a summary description of the methodology, results from the validation experiments and development of an instrument, Partial Defect Tester (PDET) that measures signal simultaneously at every guide tube to reduce measurement time within a few minutes for verification of an assembly.

1. Introduction

Spent fuel storage pools in most countries are rapidly approaching their design limits with the discharge of over 10,000 metric tons of heavy metal from global reactors. Some countries adopted a closed fuel cycle by reprocessing spent fuel and recycling MOX (mixed oxide) fuel whereas many of the countries opted for above ground interim dry storage for their spent fuel management strategy. Some countries like Finland and Sweden are already well underway in setting up a conditioning plant and a deep geological repository for spent fuel. For all these situations, transfers of spent fuel into containers are often needed and the subject spent fuel becomes to be in a 'difficult-to-access' status. According to the IAEA (International Atomic Energy Agency) Safeguards Criteria, the nuclear material should be verified prior to its becoming difficult-to-access by item counting, item identification where feasible and nondestructive assay (NDA) for partial defects. The current detection requirement for partial defect tests for irradiated fuel assemblies should assure that at least half of the fuel pins (50%) are present in each assembly. The Standing Advisory Group on Safeguards Implementation (SAGSI) recognized this problem and encouraged Member State Support Program to advance appropriate technologies for detecting pin diversion [1]. In fact, the development of a technology capable of performing partial defect tests on spent fuel assemblies has been in the IAEA R&D Program for many years [2]. However, to date, there are no safeguards instruments that can detect partial defects that meet the requirements of the IAEA, especially in an inexpensive, easy to handle setting for field application.

Lawrence Livermore National Laboratory has embarked on this challenging task and successfully developed a novel methodology in detecting removal of spent fuel rods from PWR spent fuel assemblies. The novel methodology uses thermal neutron and gamma information obtained by tiny neutron and gamma detectors inside the guide tubes of PWR spent fuel assemblies. The data obtained in such a manner provide spatial distribution of neutron and gamma fluxes within a spent fuel assembly that create unique profiles when the data are plotted against detector positions. The methodology has been proven to be effective to detect as few as 10% missing pins in an assembly, without any fuel movement and operator provided information.

2. Methodology

Every PWR fuel assembly has as a design feature a set of guide tubes where a control rod assembly can be inserted (see Figure 1.). The control rod assembly is used to control neutron flux during reactor operation. In the discharged spent fuel assembly (SFA), the guide tubes are filled with water when stored in the spent fuel pool. The concept of partial defect verification is to use the gamma and neutron flux information inside these guide tube holes to develop signature profiles that are invariant in intact SFAs.

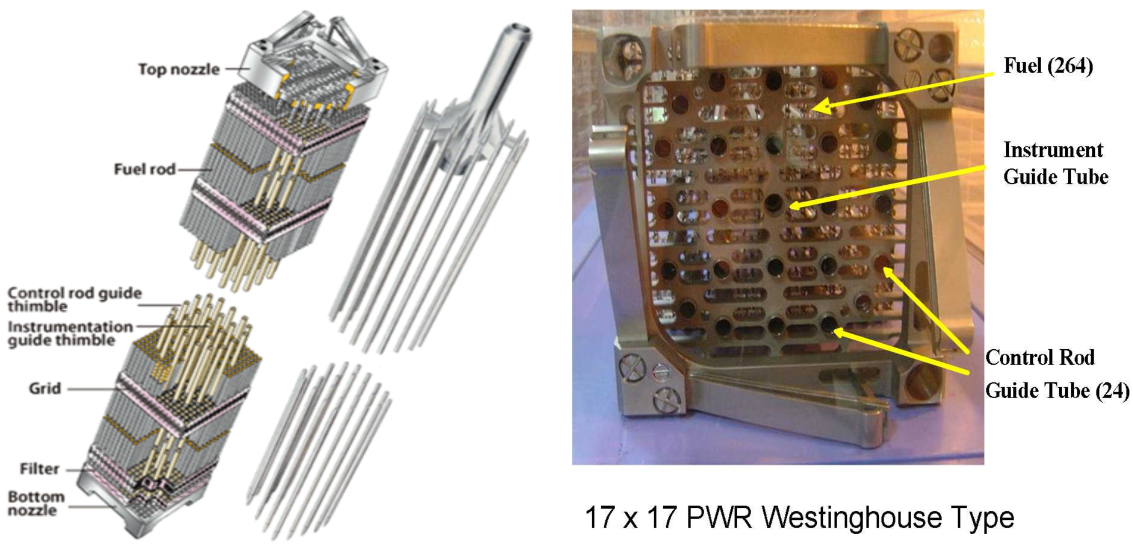

Figure 1: A schematic diagram of a pressurized water reactor fuel assembly, control rod assembly and top view of a 17x17PWR Westinghouse type fuel assembly.

The gamma and neutron signals are obtained by inserting tiny neutron and gamma detectors into the guide tubes of a SFA. The guide tubes form a quadrant symmetric pattern in the various PWR fuel product lines and the neutron and gamma signals from these various locations are processed to obtain a unique signature for an undisturbed fuel assembly, defined as the base signature. The base signatures can be formed from gamma signals, neutron signals or gamma to neutron ratio. The base gamma signature is the arrangement of the gamma signals at each of the guide tube locations normalized to the maximum among them in a particular pattern. For example, for a 14x14 PWR SFA, there are 16 guide tubes, and thus 16 measurement positions or 16 gamma data points. A symmetric pattern or base signature is obtained when gamma signals are plotted in a systematic manner starting with the guide tube location closest to the center and moving in a counter-clockwise manner for each cluster of 4 guide tubes (e.g. c, d, a, b, etc.) Figure 2 shows the alphabetic labels ‘a’ through ‘p’ for the sixteen locations. The base signatures of neutron and ratio of gamma to neutron are obtained in a similar manner. Figure 3 shows a typical base signature for the ratio when the SFA has no missing fuel pins. In the case of diversion of nuclear fuel pins, one or more of the base signatures gets distorted and the amount of distortion depends on the degree of diversion.

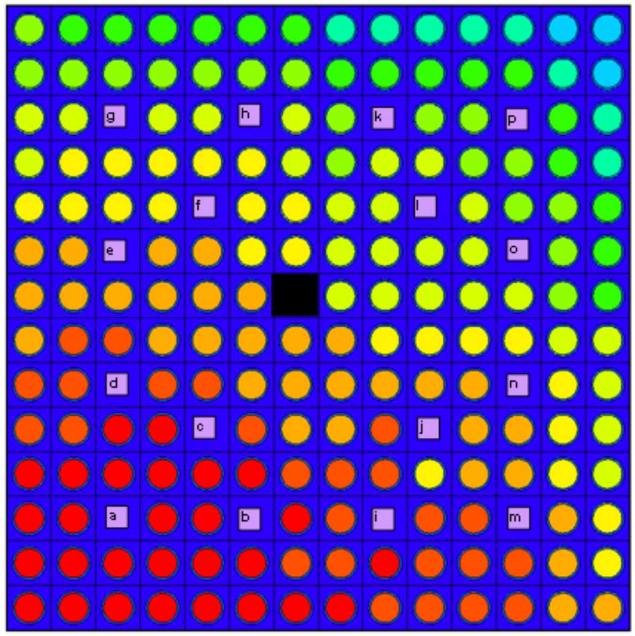

Figure 2: Fuel lattice with guide tube location

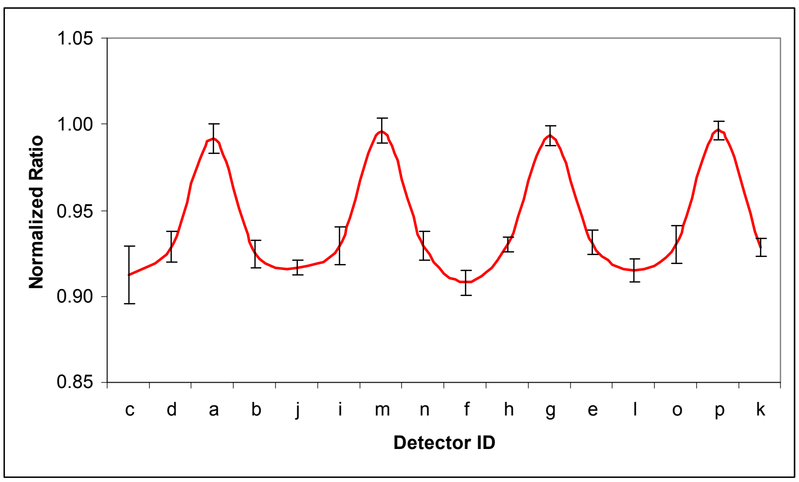

Figure 3. Typical base ratio signature produced by the normalized gamma to thermal neutron ratio

Previous papers detailed the development of this unique signature that will be noticeably perturbed if some of the fuel pins are replaced with dummy pins both in isolated SFAs as well as SFAs in an in-situ condition in the storage racks in symmetric or random removal patterns [3-8, 11]. The methodology was validated with measurements in SFAs with excellent agreement between the experimental and simulated data. Thus a visual inspection of the signature can identify partial defects, making the verification method easy to interpret without requiring operator declared data or fuel movement [9, 10, 12].

For example, the Figure 5 shows experimentally obtained measured ratio signatures for three separate spent fuel assemblies. The J14 SFA has a burnup of 37.5 GWd/tU and cooling time of 21 years, C15 SFA with 32.5 GWd/tU and 28 years, and G23 SFA with 32.5 GWd/tU and 24 years. The diagram of the three PWR fuel assemblies for which measurement data were obtained is shown in Figure 4. Red color indicates positions where rods were removed and filled with water. The signature of J14, shown in Figure 5, represents the base signature of an unperturbed assembly (only one pin missing). It is worth noting that this compares well with the simulation prediction of the base signature as shown in Figure 3. The signatures of the other two assemblies are visibly perturbed when compared to the base signature (see Figure 5). Thus diversion of nuclear fuel pins can be easily detected by simply comparing the measured signatures to the expected base signatures. Further follow up investigation needs to ensure partial defect in the case of unusual measured signatures.

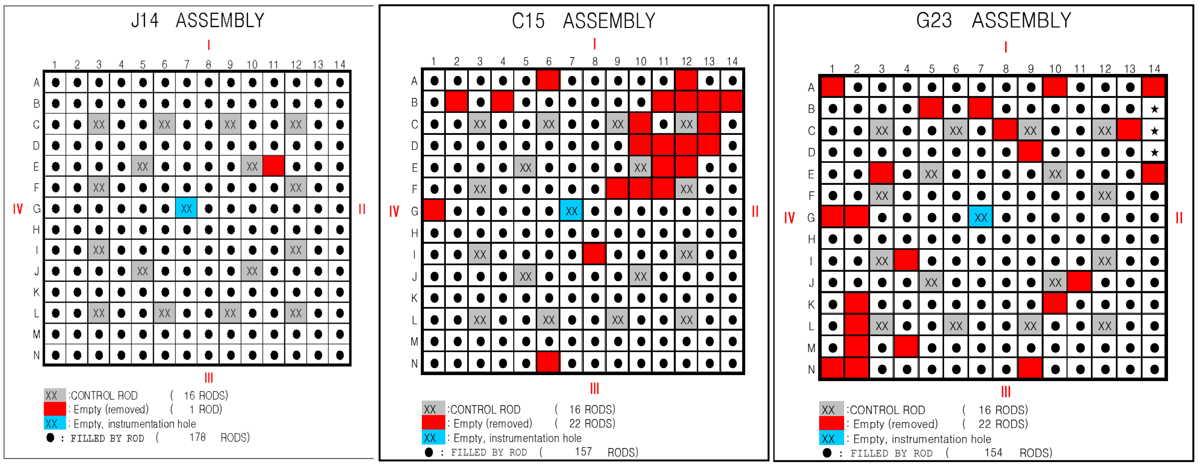

Figure 4: The diagram of fuel rod arrangement of three 14x14 PWR spent fuel assemblies (J14, C15 and G23) on which measurements were performed. Red color indicates positions where rods were removed and filled with water.

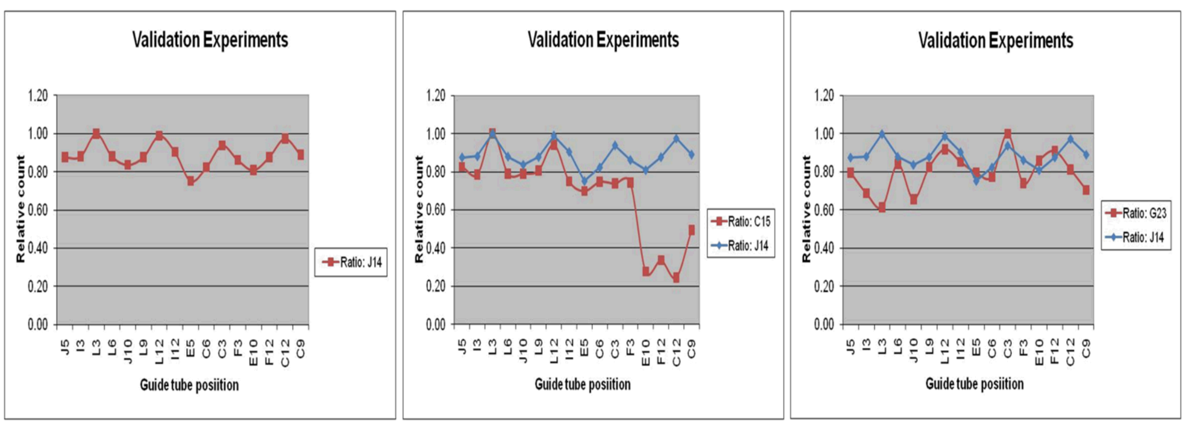

Figure 5: The base ratio signatures (gamma to thermal neutron) for three 14x14 PWR spent fuel assemblies (J14, C15 and G23). Note the deviation of the measured signature for C15 and G23 from the base signature.

Described below is a symmetric diversion case study for PWR 17x17 with uniform burnup shown in Figure 6. In this case, thirty pins, representing approximately 11% of the total active pins, are replaced with dummy fuel pins made out of stainless steel from the center of the SFA in a symmetric manner.

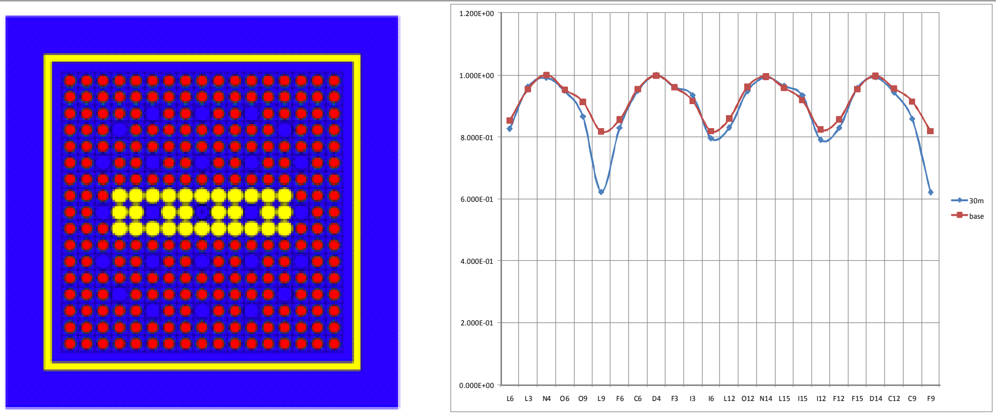

Figure 6. Schematic for the case of 30 diverted pins from a 17x17 PWR SFA (left). The right plot shows the base ratio signature in red and measured (simulated) signature for the diverted case in blue.

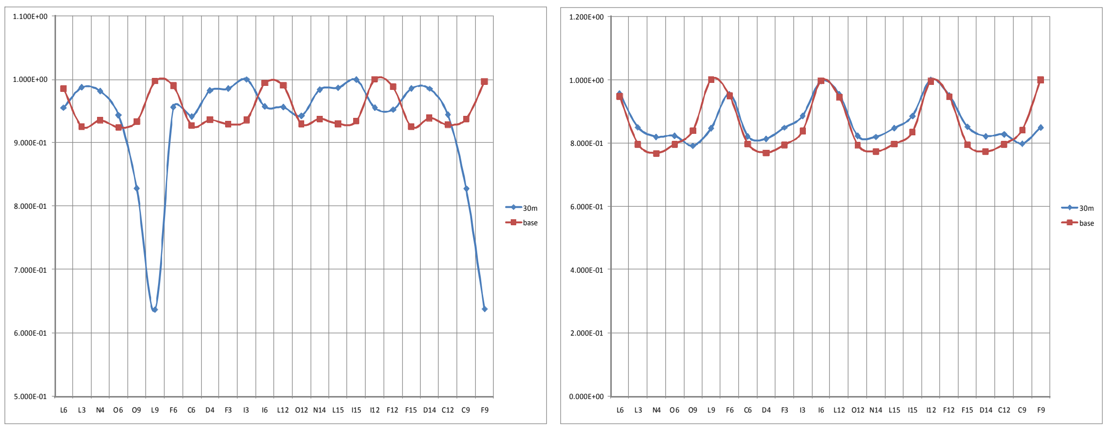

Figure 7. The left plots show the base gamma signature in red and measured (simulated) signature for the diverted case in blue. Similar plots are shown on the right for neutron.

The neutron (simulated) signature shows little variation from the base neutron signature. However, the gamma signal shows clear distortion from the base gamma signature. The two sharp drops in the gamma signal in the measured signature of gamma are due to the loss of contributions from the center pins. The perturbed gamma signature is almost a mirror image of the base gamma signature, clearly indicating diversion. As a result of these changes in the gamma signal, the ratio signature sees a more than normal peak to valley ratio. Typical peak-to-valley drops are less than 0.2 while here there is drop of 0.4. This is a secondary indication of diversion even though the overall shape remains intact in the ratio signature, being smoothed over by the neutron signal contribution at each location. Thus, all three signatures need to be examined to ensure detection of diversion.

3. PDET for PWR 17x17 Fabrication

Earlier we have reported the development of the verification methodology and validation experiments to demonstrate that the pin diversion detection methodology can be used for partial defect verification of the PWR spent fuel assemblies without the use of operator declared data. Although the results from the experiments demonstrate that the verification methodology is valid and easy to interpret data without knowledge on spent fuel, it would take an unnecessarily long time if measurement is obtained at every guide tube position one by one. In order to address this issue, PDET (partial defect tester) is being developed that has a feature of measuring signals simultaneously at multiple guide tube positions. Under development is also a data acquisition electronic system that collects all signals simultaneously in the form of pulses and processes the signals. A laptop computer is used for controlling the data acquisition system and analysis of the data to ensure no diversion has occurred.

A prototype for PDET PWR 17x17 was constructed. The prototype has a head chamber, 4 supporting rods, base plate, and 24 rodlets (the number of guide tube locations in a 17x17 SFA) that contain neutron or gamma detectors (see Figure 8). The system does not require any special tool or any sophisticated mechanism for the insertion of detectors. This is of critical importance as any safeguards instrument that IAEA uses in spent fuel pool needs to be handled by the facility operator who does not necessarily have the technical background or much time to learn to use a new tool. The PDET system is designed to be anchored visually into PWR SFA without any other insertion mechanism and the system lowered by gravity.

The prototype was tested for its insertion into a PWR 17x17 fuel assembly. The PDET was hoisted with a simple crane and slowly positioned to be anchored using outer supporting rods on an actual top nozzle plate of a PWR 17x17 fuel from Westinghouse. After the PDET was anchored, the assembly, except for the supporting rods, was slowly lowered such that all rodlets are inserted into guide tube holes. Pictures of sequential movement of PDET are shown in Figure 9.

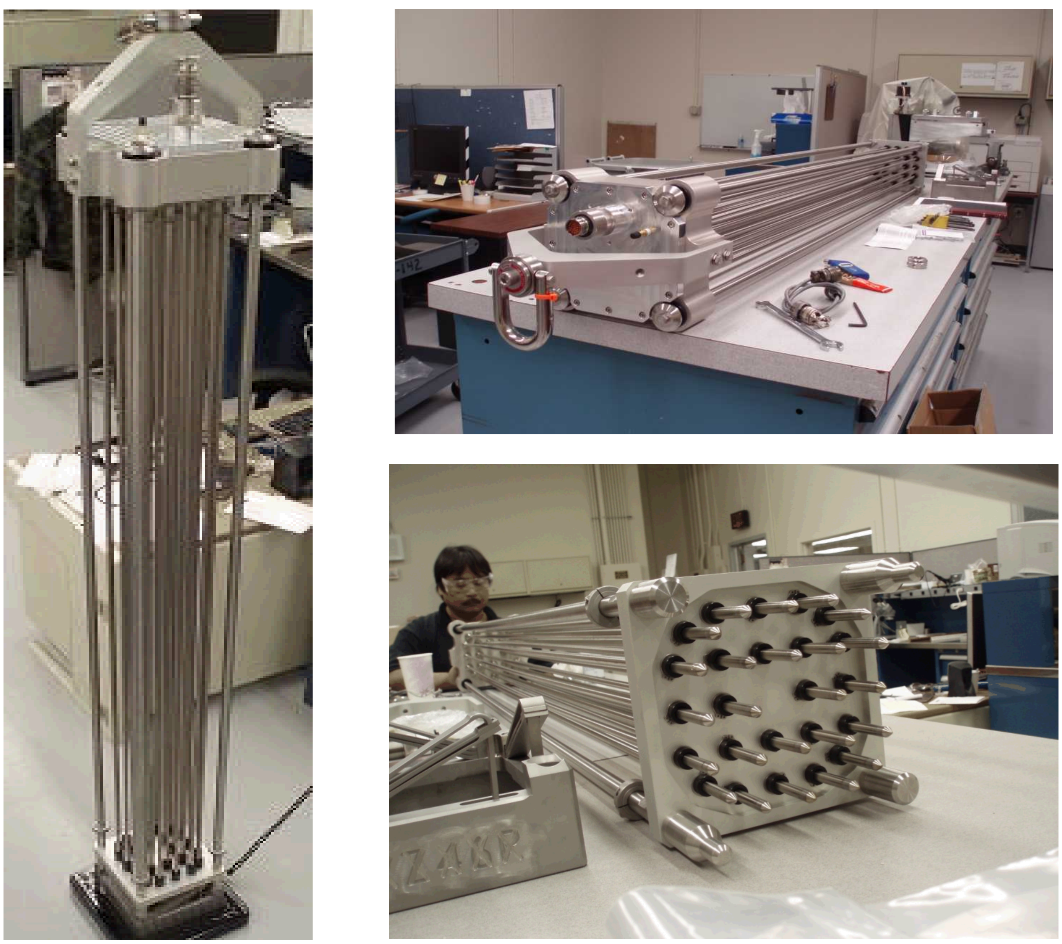

Figure 8. Pictures of PDET are shown in multiple perspectives.

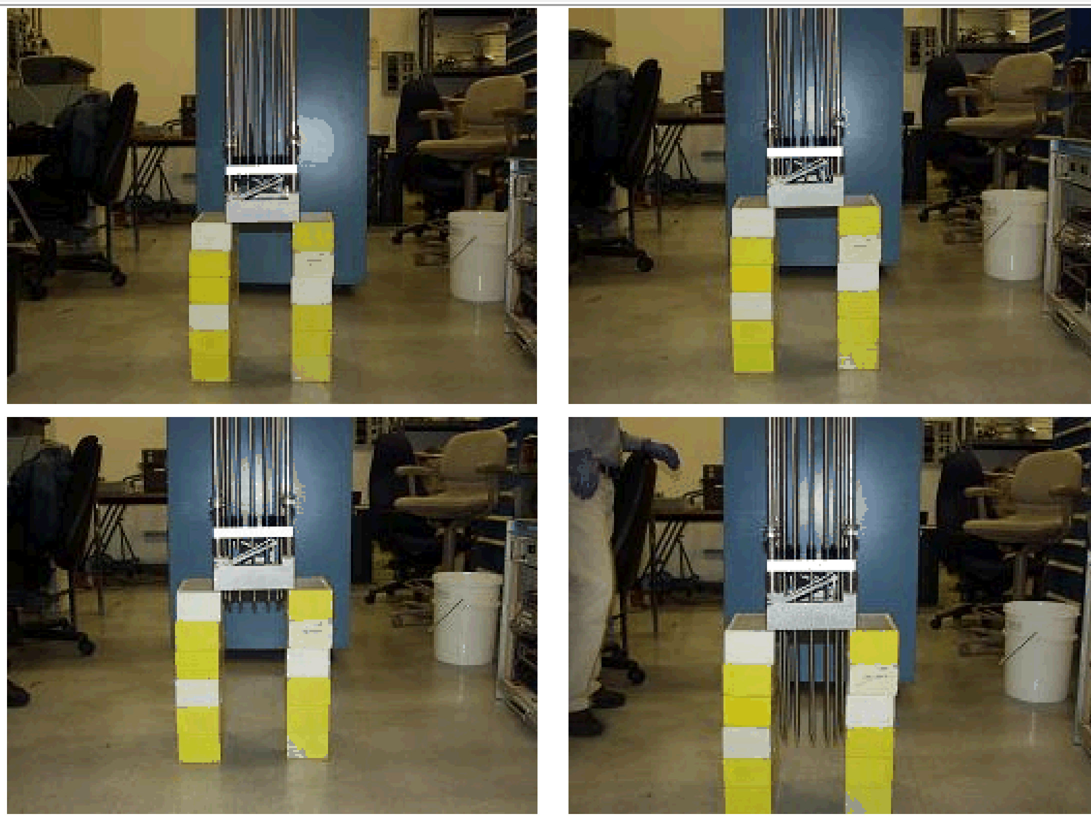

Figure 9. Insertion of a PDET into a fuel assembly is shown in time sequential pictures.

4. Summary

LLNL has developed a novel methodology in detecting partial removal of fuel from PWR spent fuel assemblies, and is actively completing a PDET system that is effective and yet practical for partial defect verification in a field environment. Simulation studies and benchmarking measurements validated the verification methodology. The envisaged PDET system would be a new powerful safeguards tool which does not require any operator provided data and that can potentially detect as low as 10% percent missing pins in an isolated or in-situ condition. This far exceeds the detection threshold of 50% missing pins from a spent fuel assembly, a threshold defined by the IAEA Safeguards Criteria.

5. Acknowledgement

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